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X-rays From Magnetic Flares In Cygnus X-1: A Unified Model With Seyfert Galaxies

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ABSTRACT

Some recent work, e.g., by Zdziarski et al., has shown that the spectrum of Seyfert 1 Galaxies is very similar to that of several Galactic Black Hole Candidates (GBHCs) in their hard state. However, several physical constraints seem to rule out the two-phase model (otherwise successful in the case of Seyfert Galaxies) for GBHCs. Here, we show that this conclusion is based on a number of key assumptions about the X-ray reflection/reprocessing within the cold disk that probably are not valid when the overlying corona is patchy, e.g., when it is comprised of localized magnetic flares above the disk. We find that if the X-rays are emitted within these magnetic structures atop the cold disk, then the X-ray reflection/reprocessing of the primary X-rays by the latter is *not* scale-invariant with respect to the black hole mass. In particular, we show that in GBHCs the energy deposited by the X-rays cannot be re-radiated fast enough to maintain equilibrium, unless the X-ray skin heats up to the Compton temperature, at which point the gas is mostly ionized. This leads to a substantially reduced cooling rate for the active regions due to the correspondingly smaller number of re-injected low-energy photons. We model this effect by introducing a transition layer situated between the corona and the cold disk, and find that the resulting spectrum is harder than that obtained with the standard (and unrealistic) two-phase model. We apply this model to Cygnus X-1 and show that it *can* account for its observed spectrum. This analysis therefore seems to provide a consistent picture for both Seyfert Galaxies and GBHCs within the same framework, with differences arising due to the changing physical conditions in the two categories of sources, rather than due to an *ad hoc* variation of the model parameters.

Subject headings: accretion disks — black hole physics — Cygnus X-1 — galaxies: Seyfert — magnetic fields — radiative transfer

1. Introduction

The progress made in recent years in understanding the X-ray spectra of Seyfert Galaxies and Galactic Black Hole Candidates (GBHCs) indicates that the reflection and reprocessing of incident X-rays into lower frequency radiation is an ubiquitous and important process. For Seyfert Galaxies, the X-ray spectral index hovers near a "canonical value" (~ 0.95; Pounds et al. 1990, Nandra & Pounds 1994; Zdziarski et al. 1996), after the reflection component has been subtracted out of the observed spectrum. It is generally believed that the universality of this X-ray spectral index may be attributed to the fact that the reprocessing of X-rays within the disk-corona of the two-phase model leads to an electron cooling rate that is roughly proportional to the heating rate inside the active regions (AR) where the X-ray continuum originates (Haardt & Maraschi 1991, 1993; Haardt, Maraschi & Ghisellini 1994; Svensson 1996). It has been suggested that the ARs are probably magnetically dominated structures, i.e., magnetic flares (Haardt et al. 1994; see also Galeev, Rosner & Vaiana 1979).

GBHCs have similar, though considerably harder, spectra and a reflection component less prominent than that of Seyfert Galaxies (Zdziarski et al. 1996). Indeed, Rossi X-ray observations of Cygnus X-1 show no significant evidence for a reflection component (Dove et al. 1997a). It is the relatively harder spectrum and the small reflection component (together with other more subtle arguments) that led Dove et al. (1997a,b), Gierlinski et al. (1997) and Poutanen, Krolik & Ryde (1997) to conclude that the two-phase patchy corona model does not apply to Cygnus X-1 – arguably the best studied GBHC. Physically, the harder spectrum of GBHCs requires a much lower cooling rate than can be expected in the two-phase model. However, as we shall show below, this conclusion relies heavily on the assumption that the reflection/reprocessing process in the GBHCs is similar in nature to that of the higher mass Seyfert nuclei. In view of the fact that in most situations the accretion disk physics is black hole mass-invariant, this at first appears to be a reasonable assumption (but see Ross, Fabian & Brandt 1996).

In this *Letter*, we point out that previous studies of the X-ray reflection process (e.g., Sincell & Krolik 1997; Magdziarz & Zdziarski 1995; and additional references cited in Nayakshin & Melia 1997a) have concentrated on a static, full corona, a model that is unlikely to work even for Seyfert Galaxies (e.g., Haardt et al. 1994; Svensson 1996). Motivated by this fact, Nayakshin & Melia (1997a; hereafter paper I) investigated the X-ray reflection process in AGNs assuming that the ARs are magnetic flares above the disk. These flares are short lived (see below), and the properties of the *transient* X-ray reflection turn out to be similar, and yet different enough from the static reflection process, to provide an interesting explanation

for the narrow range in the observed temperature of the Big Blue Bump and the low degree of ionization in the underlying disk.

It is therefore important to consider the physics of reflection in the two-phase model for GBHCs with transient ARs, paying particular attention to aspects of this process that are not scale-invariant with respect to the black hole mass M. Below we show that a transient X-ray irradiation of the disk may account for the differences in the reflected fraction and the overall spectrum of Seyfert Galaxies and GBHCs. We find that the X-ray skin in GBHCs is much hotter and more strongly ionized than that in Seyfert nuclei, and is probably at the local (optical depth dependent) Compton temperature. It therefore acts as a "transition" layer in the case of GBHCs. This is in contrast to the situation in static X-ray reflection models, where the pressure equilibrium condition in this skin is black hole mass-invariant and leads to a cooler and far less ionized plasma.

As we shall see, the reflection process in a transition layer held at the Compton temperature substantially reduces the Compton cooling rate within the corona due to the upscattering of reprocessed radiation. We present several test results indicating that the presence of this transition layer, heated and cooled by Compton scattering with the hot coronal and cold disk radiation leads to a spectrum that is much harder than that of the standard two-phase model. Our results demonstrate that a consideration of the structure of the X-ray skin in a realistic two-phase model may therefore remove many current inconsistencies of the coronal picture with observations. We point out that the two-phase model with magnetic flares as the particle energizing mechanism in active regions may constitute a single explanation for both Seyfert nuclei and GBHCs, and account for differences in their spectra self-consistently.

2. Transient X-ray Reflection For GBHCs

As shown in paper I, the main characteristic of transient reflection, distinguishing it from its well-studied static counterpart, is that magnetic flares can only be active during a disk hydrostatic time scale. It is not difficult to show (e.g., using the model of Svensson & Zdziarski 1994) that the photon diffusion time across the disk is much longer than this for both radiation and gas-dominated disks. Therefore, no thermal equilibrium can be established between the underlying cold disk and the incident X-radiation during the flare. Instead, a quasi-equilibrium is established within an X-ray skin with Thomson optical depth $\tau_{\rm T} \sim$ few. It is this X-ray skin that plays the major role in reprocessing and reflecting the incident X-rays. We should further refine our definition of the X-ray skin (or transition layer) by specifying that this layer

corresponds only to that part of the disk's upper region below or close to a magnetic flare, i.e., within a few scale heights of the AR, since that is where most of the X-ray reprocessing will occur. Thus, the X-ray skin is a transient phenomenon: it comes into existence due to the illuminating X-ray flux from the AR, so it lasts only as long as the flare persists.

Under the very intense incident X-ray flux, the upper layer of the disk in Seyfert nuclei contracts to a high density, which allows the irradiated gas to emit the deposited energy efficiently due to the strong density dependence of the optically thin free-free process (e.g., Rybicki & Lightman 1979). However, as was noted in paper I, this treatment is valid only when the X-ray skin is optically thin to free-free emission. Using a Rosseland mean free-free optical depth and Equation (4) of paper I, it is straightforward to see that the free-free optical depth of the X-ray skin is $\tau_{\rm ff} \simeq 5 \times 10^{-5} (\tau_{\rm T}/3)^2\, l_2^2\, \Delta R_{13}^{-1} T_6^{-7/2}$, where $l \equiv 100\, l_2 \sim 100$ is the compactness parameter of the AR, T_6 is the electron temperature in units of 10^6 K, and $\Delta R_{13} \equiv \Delta R/10^{13}$ cm is a typical size of the AR, expected to be of the order of the disk scale height. In Seyfert nuclei, $\tau_{\rm ff}$ is very much smaller than unity, validating the optically thin approximation. However, rescaling the parameters for the case of GBHCs with a mass $\sim 10\, M_\odot$, we obtain

$$\tau_{\rm ff} \simeq 500 \times (\tau_{\rm T}/3)^2 \frac{l_2^2}{\Delta R_6} T_6^{-7/2} \; . \tag{1}$$

The most straightforward way to modify this result would be to simply assume blackbody emission, but this approach would be incorrect since the X-ray skin cannot consistently be optically thick and in pressure equilibrium, as we now will show. The latter is set up between the incident X-ray (ram) pressure and the internal skin pressure, with contributions from both the gas and the reprocessed radiation, which was neglected in paper I. In Seyfert nuclei the skin's internal gas and radiation pressures are comparable, but in GBHCs the radiation pressure would be dominant since a typical photon suffers many absorption/emission events before escaping from the gas. In equilibrium, the internal radiation pressure must be smaller than the external X-ray pressure, so that

$$\tau F_{\rm bb}/c \lesssim F_{\rm x}/c \; , \tag{2}$$

where $F_{\rm x}$ is the incident X-ray flux from the AR, τ is the total optical depth of the X-ray skin, and $F_{\rm bb}$ is the blackbody flux out of the transition layer. On the other hand, if the incident energy is reradiated out of the transition layer, one should expect that

$$2F_{\rm bb} \sim F_{\rm x} \; , \tag{3}$$

where the factor 2 arises because the radiation can escape in both the upward and downward (i.e., toward the disk midplane) directions. Thus, unless $\tau \lesssim$ few, a self-consistent equilibrium is not possible.

So what does happen in the irradiated layer in physical terms? The incident X-rays, being too energetic (most of the flux in Cygnus X-1 is at > 20 keV), are not absorbed via free-free absorption if the gas temperature is $T \ll$ few keV. Under these conditions, the X-rays would penetrate unimpeded into the skin to a Thomson optical depth $\sim$ few, just as in the static case. Accordingly, irrespective of how large $\tau_{\rm ff}$ is, the incident X-rays would heat the upper region of the disk with $\tau_{\rm T} <$ few. However, the down-scattered X-rays, and the UV to soft X-ray photons due to internal emission would be readily absorbed and could not escape fast enough from the X-ray layer. Therefore, we have a situation where the energy penetrates into the skin easily, but cannot leave due to multiple absorption/emission events (one should recall that blackbody radiation is appropriate only when an average photon scatters many times before it escapes), and thus no equilibrium between heating and cooling can be established. As the reprocessed radiation builds up inside the X-ray skin, it reaches the point where its pressure exceeds the external X-ray ram pressure, and the X-ray skin expands, becoming hotter and less dense. Correspondingly, the free-free emissivity drops, and the X-ray skin cannot keep up with the energy deposition rate. The heating process itself, however, has its limitations: at the local Compton temperature (i.e., about 15 keV) the radiation field does not transfer any net energy to the gas by inverse Compton interactions. The gas simply *reflects* most of the incident X-rays, rather than absorbing and reprocessing them into the UV range.

This contrasts with the static case, in which the nature of the pressure equilibrium within the X-ray skin is quite different (Sincell & Krolik 1997). Here, the transient illuminating X-ray flux $F_{\rm x}$ is much larger than in the static case, because the same fluence (i.e., integrated flux) must now be produced from a smaller coronal region and, in addition, the ARs are only active for a short time. Taken together, these lead to a larger ionization parameter $\xi_{\rm x} \simeq 2.5 \times 10^3 (F_{\rm x}/cP_{\rm gas})$, where $P_{\rm gas}$ is the gas pressure within the X-ray skin (see, e.g., Eq. 3.1 of Zycki et al. 1994). Since $P_{\rm gas}$ is certainly smaller than $F_{\rm x}/c$, $\xi_{\rm x}$ is very large, and the GBHC X-ray skin is therefore in the "limit of a hot medium" (see §3.1 of Zycki et al. 1994). The fact that this segment of parameter space is unlikely to be reached in a static corona is probably the reason why the spectroscopic consequences of reflection in a Compton equilibrium medium have not been considered earlier. We take up this question in the following section.

3. "Three-Phase" Model

Hereafter, we shall assume that the X-ray skin attains its *local* Compton temperature. We conduct several representative tests which will allow us to understand the important physics of the model, without

necessarily attempting yet to fit any particular spectrum of a GBHC. Our model consists of an active region above the (heated) transition layer. The geometry of the AR is probably closer to a hemisphere than a slab, but for simplicity we shall adopt the latter for the radiation transport, neglecting the boundary effects. However crude, this approximation is adequate for our purposes. Experience has shown that spectra produced by Comptonization in different geometries are usually qualitatively similar (i.e., a power-law plus an exponential roll-over), and it is actually the fraction of soft photons entering the corona that accounts for most of the differences in the various models, because it is this fraction that affects the AR energy balance.

Following the standard practice in ionization/reflection calculations, we model the reflecting medium as being one dimensional, with its only dimension being the optical depth into the disk (measured from the top). Nevertheless, we have to take into account the fact that the patchy corona geometry permits some part of the reprocessed radiation to re-enter the corona, whereas the rest escapes to the observer directly. Accordingly, the observed spectrum consists of the direct component, emerging through the top of the corona (AR), and a fraction Ω of the reflected radiation that emerges from the transition layer and does not pass through the corona on its way to us. A fraction $g = 0.5$ of the reflected spectrum goes back into the corona through its bottom (cf. Poutanen & Svensson 1996). Below the transition layer lies an optically thick portion of the disk with Thomson optical depth $\tau_{\rm T} \gg 1$, held at a temperature $T_{\rm bb} = 100$ eV. We employ the Eddington (two-stream) approximation for the radiative transfer in both the AR and the transition layer, using both the zero (isotropic) and first order moments of the exact Klein-Nishina scattering kernel (Nagirner & Poutanen 1994). The optical depth of both the transition layer $\tau_{\rm trans}$ and the corona $\tau_{\rm c}$ are treated as parameters; $\tau_{\rm c}$ is fixed at an arbitrarily chosen value of 0.7 for the purpose of demonstrating the main point. In a generally accepted setup for the two-phase model, the transition layer is absent, and the X-rays incident on the cold disk below the AR are partially reflected ($10 - 20$ %), while the rest are reprocessed and re-radiated as blackbody radiation. In the tests reported here, the incident X-rays are first scattered within the transition layer, as we self-consistently calculate the spectrum that is incident on the cold disk after the original spectrum from the AR passes through the layer. The spectrum incident on the cold disk from the transition layer is reflected and reprocessed in the standard manner (Magdziarz & Zdziarski 1995), and then re-enters the transition layer from below. We assume a coronal heating rate much exceeding the local intrinsic disk flux and find the radiation field and the self-consistent temperature in both the corona and in the transition layer as a function of the optical depth.

Figure 1 shows the "observed" spectrum for several values of $\tau_{\rm trans}$: 0, 0.6, 2.5, and 10, with $\Omega = 0.5$. It can be seen that the spectrum hardens as $\tau_{\rm trans}$ increases. To help explain why this happens, we plot in

Figure 2 the integrated albedo a for photons with energy $E > 1$ keV as a function of $\tau_{\rm trans}$. The albedo is simply the inverse ratio of the incident flux in the given energy range to the returning one, i.e., that emerging from the top of the transition layer. As $\tau_{\rm trans}$ increases, a large fraction of the photons from the AR are reflected before they have a chance to penetrate into the cold disk where the blackbody component is created. Therefore, a smaller flux of energy is deposited below the transition layer, which leads to a decreased cooling from the Comptonization of soft, reprocessed radiation. For a moderate optical depth $\tau_{\rm trans}$, this result is quite insensitive to the temperature in the transition layer as long as Fe is highly ionized. We checked this by simply setting the transition temperature at the arbitrarily chosen values of 1.5 and 6 keV, instead of the self-consistent temperature distribution calculated above, which varied (with optical depth into the transition layer) from about 2 to 4 keV for the respective values of $\tau_{\rm trans}$. We found that the relative variations in the spectrum and the albedo resulting from this were less than about 3 %. For higher optical depths ($\tau_{\rm trans} \gtrsim 4$), pre-Comptonization of the soft disk radiation becomes important and additionally decreases the Compton cooling of the corona by this component, so that the temperature of the transition layer becomes essential.

Figure 3 shows the observed spectrum (solid curve), comprising the intrinsic AR spectrum (short-dash) and the reflected component (emerging from the top of the transition layer; dotted curve) multiplied by $\Omega = 0.5$. Also shown is the reprocessed component at the base of the transition layer (long-dash). All the intensities propagate in the upward direction. Notice that due to the presence of the transition layer, the reflected component is much harder than the reprocessed component, which would be the "normal" reflection/reprocessing component without this layer. Notice also that the bump around ~ 40 keV normally attributed to the reflected component is broad (compared with the long-dashed curve), and so the reflected component is here less noticeable.

Furthermore, the combined power below 2 keV accounts for only 25 % of the total, whereas the corresponding fraction is about 50 % in the standard (static) two-phase model. This large power coming out in low energy photons was the main reason why the standard two-phase corona-disk model failed to account for the observations. The large soft photon power is not only not observed in the Cygnus X-1 spectrum, it also provides too much cooling for the Active Regions, and their spectra are never hard enough. In the time-dependent situation these problems are resolved because of the structure of the transition layer, as we described above.

The transition layer may be thought of as a partially transparent mirror. Crudely, some of the photons

are scattered back without a change in energy, and the rest proceed to the cold disk and suffer the usual transformation into soft disk photons. Photons downscattered in the transition layer before they return to the corona do not contribute to the cooling because the energy gained by an electron in the layer is later used to upscatter the softer photons coming from the cold disk (whereas in the cold disk case this energy would be used to produce the soft radiation).

The spectral calculations reported here could also be appropriate for the static patchy corona model if the upper layer of the disk was hotter than usually assumed. Indeed, it is not hard to imagine that the upper layer is being heated in a way similar to heating of the Solar corona. If the temperature of the layer is few keV and its Thomson optical depth is close to ~ 3, then the spectra produced in this situation may be close to the observed hard spectra of the GBHCs. It is not clear to us why this possibility has never been explored by previous workers. At the same time, even if such a static model could remove the problems for the GBHCs spectra, one would need to explain why the upper layer of the disk in Seyfert Galaxies is not being heated to similar temperatures. Thus, the real strength of the magnetic flare model of the active regions is in the fact that this is the same physics that explains spectra of both Seyfert Galaxies and GBHCs.

4. Discussion

By considering the equilibrium structure of the irradiated X-ray skin close to an active magnetic flare above a cold accretion disk, we have shown that neither the optically thin free-free emission process or the black body radiation can consistently comply with pressure equilibrium constraints in the X-irradiated skin of GBHCs. Thus, in sharp contrast to the transient X-ray reflection process in Seyfert nuclei (paper I), the X-ray skin achieves *Compton equilibrium* ($kT \sim$ few keV) with the incident X-radiation. As a result, most of the incident X-rays are Compton reflected back into the AR before reaching the cooler disk material where reprocessing into a soft-excess component occurs. Accordingly, the amount of cooling due to the soft radiation re-entering the AR is drastically reduced and this allows the two-phase model with magnetic flares to reach the parameter space necessary to explain the observed X-ray spectrum of Cygnus X-1.

The consequences of this "three-phase" structure include the following: (1) GBHC spectra should be harder than those in typical Seyfert 1s. For $\tau_{\rm trans} \gg 1$, the spectrum may be somewhat different from that of single cloud Comptonization plus a reflection component, especially in the region of $\sim 30 - 200$ keV, which is not inconsistent with data (see Fig. 3 and Gierlinski et al. 1997). (2) The observed soft X-ray

excess should contain comparatively less power than the hard component, in contrast to Seyfert 1s. (3) The Thomson optical depth of the flares should be similar in GBHCs and Seyfert Galaxies, and therefore so should the electron temperature within their ARs (see Nayakshin & Melia 1997b; this aspect of the model does not depend on M). (4) No anisotropy break should be seen in the spectrum due to the input "soft" radiation not being a blackbody and entering the ARs sideways (in accordance with observations; see, e.g., Gierlinski et al. 1997). As was discussed in Poutanen & Svensson (1996), the anisotropy break occurs where the second order scattering peaks. However, as we found from our numerical results, the anisotropy break disappears as the optical depth of the transition layer increases. The reason for this is physically transparent: the reflected continuum is no longer the blackbody emission (which was assumed by Gierlinski et al. 1997, and Poutanen & Svensson 1996) and is quite broad. Compton scattering broadens any initial photon distribution, and therefore the second order scattering of the reflected continuum becomes a very diffuse function, with a shallow peak. Among other effects that should reduce the anisotropy break is the stratified temperature distribution below the AR and its dependence with distance from the flare. The cold disk emission will then be a sum of black bodies with different temperatures, and will be even broader than what we assumed in our calculations. Earlier contrasting results found by Gierlinski et al. (1997) may be due to an oversimplification of the cold disk structure and emission. (5) The reflected component in the observed spectrum must be less pronounced or not observable, depending on the transition layer optical depth. (6) The Fe lines from the inner accretion disk should be either weak or broad and thus indistinguishable from the continuum due to Comptonization within the transition layer. The observed weak Kα line may then be arising from the cold outer disk. (7) The same is true for the Fe edge. Note that observationally, it is very hard to detect a broad Fe edge in the case of Cygnus X-1 (Ebisawa 1997, private communication). (8) X-ray variability should be observed on a time scale of the order of the disk hydrostatic time scale, i.e., $\sim$ milliseconds. Since one separate flare lives only a few milliseconds, the hard and soft X-rays should vary instantaneously down to a fraction of this, i.e. 1 millisecond or so. Therefore, the observed high coherence of the hard and soft X-rays in GBHCs (e.g., Vaughan & Nowak 1997) is a natural consequence of the model.

Although a more detailed spectral modeling is needed to confirm many of these predictions for the hard state spectrum in GBHCs, even the simple treatment used here shows that the two-phase model with magnetic flares as ARs may ultimately account for both the characteristics of Seyfert Galaxies and GBHCs. Very importantly, it explains the differences in the spectra of these two classes of objects self-consistently, i.e., based solely on the physics of the irradiated region at the surface of the disk, rather than as a result of

an *ad hoc* variation of the parameters.

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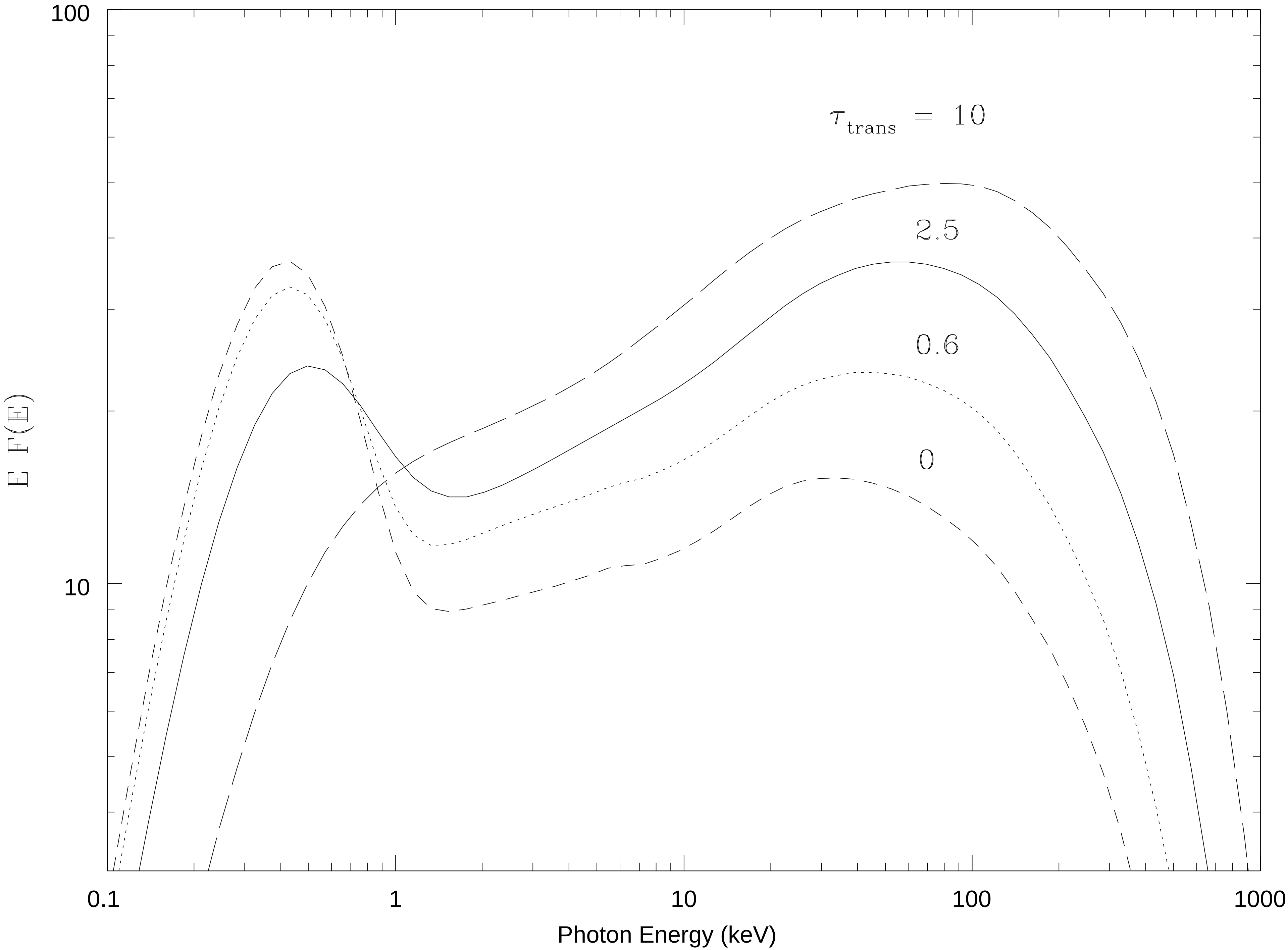
Fig. 1.— The "observed" spectrum for various values (marked) of the transition layer optical depth, $\tau_{\rm trans}$.

Fig. 2.— Integrated albedo (reflected fraction) as a function of the transition layer optical depth, $\tau_{\rm trans}$, for photons with energy > 1 keV. Also plotted (dotted curve) is the ratio of the observed hard luminosity (above 2 keV) to the observed total luminosity. Note that the transition layer reflects a greater fraction of the photons as $\tau_{\rm trans}$ increases, and the spectrum correspondingly hardens.

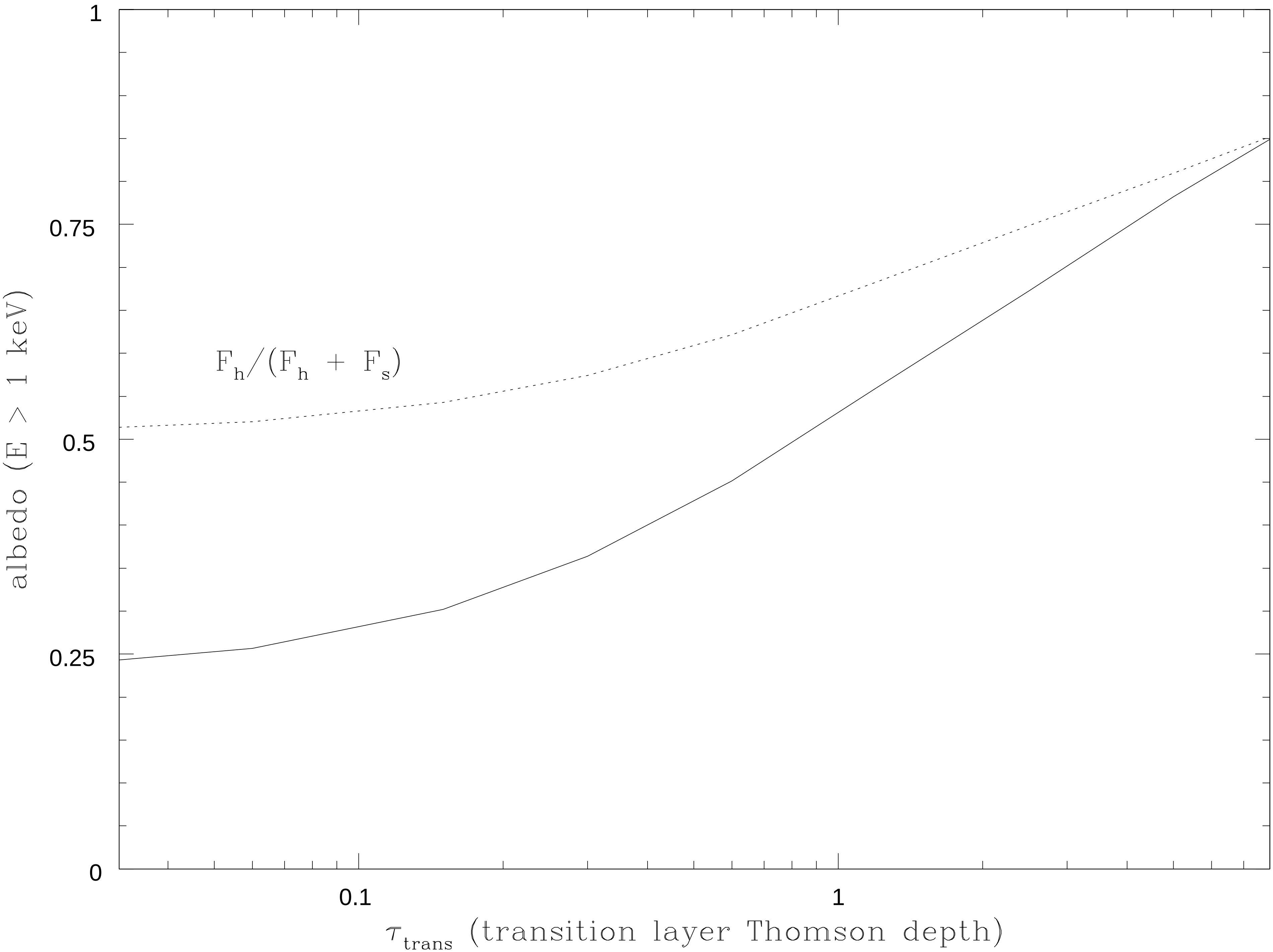
Fig. 3.— Decomposition of the observed spectrum (solid curve) into its essential components: the intrinsic AR spectrum (short-dash) plus the reflected component (emerging from the top of the transition layer; dotted curve) multiplied by $\Omega = 0.5$. The reprocessed component at the base of the transition layer is also shown by the long-dashed curve. See text for a further discussion.

Figure 1



τ_{trans} = 10
2.5
0.6
0
E F(E)
Photon Energy (keV)
100
10
0.1
1
10
100
1000

Figure 2



1
0.75
0.5
0.25
0
0.1
1
albedo (E > 1 keV)
$F_h/(F_h + F_s)$
τ_{trans} (transition layer Thomson depth)

Figure 3